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Abstract

Electron cooling of completely stripped gold ions $^{197}\mathrm{Au}^{79+}$ in RHIC is considered for the store energy, $\gamma = 108$. The optimal parameters of the required electron storage ring are discussed and proposed. The cooling time is calculated as 15 minutes, which would allow not only to avoid the beam loss due to the intra-beam scattering, but also reduce the transverse emittance and increase the luminosity several times.

1 Cooling Rates

The electron cooling suggested by Budker [1] (the most recent review is [2]) was experimentally proved as an effective method to get bright non-relativistic ion beams. Up to now, it has never been realized in the relativistic region, $\gamma \gg 1$. Below, a possibility of using it for the fully stripped gold beam in RHIC at $\gamma = 108$ is considered. Electron cooling at the required energy needs a circulated bunched electron beam: a machine capable of delivering ~ 1A DC does not exist at this energy. Ion cooling times can be found by means of the standard formulae, in the result of an integration over the electron distribution and averaging over the betatron and synchrotron phases of the ion, as in [3]. The longitudinal $\tau_\parallel^{-1}$ and transverse $\tau_\perp^{-1}$ cooling rates are determined as logarithmic derivatives of the corresponding ion emittances:

$$\begin{aligned}\tau_{\|}^{-1} &= \frac{1}{\delta_{iE}\sigma_{is}}\frac{d}{dt}(\delta_{iE}\sigma_{is}) = \frac{2}{\delta_{iE}}\frac{d\delta_{iE}}{dt} \\ \tau_{\perp}^{-1} &= \frac{1}{\epsilon_{in}}\frac{d\epsilon_{in}}{dt}\end{aligned} \tag{1}$$

where δ_{iE} is the rms relative energy deviation (= relative energy amplitude/$\sqrt{2}$), σ_{is} is its rms longitudinal offset (= amplitude/$\sqrt{2}$), ϵ_{in} is the normalized rms emittance of the ion. The calculations are simplified when the transverse ion velocities in the beam frame are high in comparison with the longitudinal one; in this case it is:

$$\begin{aligned}\tau_{\|}^{-1} &= \frac{2N_e r_e r_i \eta_c c}{\pi\gamma^2\sqrt{\sigma_{is}^2+\sigma_{es}^2}}\left(\frac{\exp(-2\epsilon_{in}/\epsilon_{en})L_{\|}}{\epsilon_{en}^2\sqrt{\delta_{iE}^2+\delta_{eE}^2}} + \frac{L_{\perp}}{4\epsilon_{in}^2}\sqrt{\frac{\beta_c}{\gamma\epsilon_{in}}}\right) \\ \tau_{\perp}^{-1} &= \frac{N_e r_e r_i \eta_c c L_{\perp}}{\pi^2\gamma^2(\epsilon_{in}^2+\epsilon_{en}^2)\sqrt{\sigma_{is}^2+\sigma_{es}^2}}\sqrt{\frac{\beta_c}{\gamma\sqrt{\epsilon_{in}^2+\epsilon_{en}^2}}}\end{aligned} \tag{2}$$

Here N_e is the number of electrons in the electron bunch, r_e and r_i are the electron and ion classical radii, η_c is the fraction of the ion ring occupied by the cooler, δ_{eE} and σ_{es} are the electron rms relative energy spread and bunch length, ϵ_{in} and ϵ_{en} are the ion and electron normalized rms emittances, c is the speed of light, β_c is the ion beta-function in the cooler, $L_{\|}$ and $L_{\perp}$ are the Coulomb logarithms calculated with the longitudinal and transverse relative ion-electron velocities correspondingly. The ion and electron transverse emittances for the both degrees of freedom were assumed here to be equal. This assumption is normally reasonable for ion beams, while electron beams are typically flat, being dominated by the horizontal emittance. If so, the displayed results (2) can serve as an estimate with the horizontal electron emittance as the parameter ϵ_{en}.

It follows from this that for a given ion emittance the rates reach their maxima at $\epsilon_{en} \simeq \epsilon_{in}$. To prepare such a cold beam with sufficiently high number of particles appears to be not feasible by means of a conventional techniques. Recently, a specific optical scheme was suggested to resolve this problem [4, 5].

2 Adapter

The main idea of this scheme is to transform the flat electron beam with a high horizontal temperature into a beam with a certain nonzero cross-section and low temperature determined by the small vertical emittance of the beam in the entrance. In other words, it is a transformation of $x-x'$ phase volume into $x-y$ one, while $y-y'$ is transformed into $x'-y'$. This transformation does not change the product of the transverse phase volumes ($4D-$volume), but optimally shapes it to fit the phase space occupied by the ion beam.

One of the schemes of this insertion was presented in [5]. The device consists of two parts: a skew block consisting of three quadrupoles turned at 45°, followed by a solenoid. The skew block transforms the plane beam into a helix with the transverse velocity perpendicular to the coordinate vector for all the points. Then, the kick at the solenoid entrance eliminates this vortex motion due to the matching of the magnetic field. Generally, the electron beam cross-section inside the solenoid is found to be elliptical; in particular, the shape is round when the Larmor length in the solenoid $\beta_s = pc/eB$ is matched with the electron horizontal beta-function at the adapter entrance, $\beta_s = \beta_{xe}/2$. In this last case, the beam rms radius inside the solenoid is $1/\sqrt{2}$ of the rms horizontal size at the entrance of the adapter, while its rms angle θ_e is determined by the small (normalized) vertical emittance at the entrance, ϵ_{ny}:

$$\theta_e^2 = \epsilon_{ny}/(\gamma\beta_s). \tag{3}$$

In addition to this shaping of the electron phase volume, another aim is reached: an electron beam is strongly focused by the magnetic field in the cooling section without any damage to its temperature. In the following, the emittance ratio $K = \epsilon_{ny}/\epsilon_{nx}$ is assumed to be small: $K = 0.5 \cdot 10^{-2}$.

3 Electron Beam Population and Energy Spread

The electron bunch population N is limited by the Laslett tune shift:

$$\Delta\nu_L = \frac{N r_e \bar{R}}{\gamma^2 \sigma_{es} \sqrt{2\pi \epsilon_{nx} \epsilon_{ny}}} \leq 0.1 \tag{4}$$

where $\epsilon_{nx},\ \epsilon_{ny}$ are normalized horizontal and vertical rms emittances beyond the cooling section. For the given (optimal) emittance ϵ_{nx}, the bunch linear density is fixed by this limit. The optimal choice of the electron bunch length is somewhat higher than the ion one; $\sigma_{es} = 1.5\sigma_{is}$ is almost at the rates saturation over this parameter.

To reach the maximum longitudinal cooling, the electron energy spread has to be smaller than the ion one. Otherwise, the dominant first term in the longitudinal rate of Eqs. (2) would be smaller than its maximum at the given ion energy spread. To achive this goal, the radiation cooling of the electron beam has to be high enough to keep electrons longitudinally cool under the action of the electron-electron and eletcron-ion intra-beam scattering (IBS) as well as the radiation quantum fluctuations. That is why a rather strong and long wiggler is needed.

The contribution of the electron-ion IBS (electron heating in the cooler) strongly depends on the ion charge, $\propto Z_i^2$. This heat loading would be enormous for a single electron bunch, so a multi-bunch electron beam is required to share this heating between all of them. The maximal number of bunches is determined by the electron ring circumference. In the optimum case, the contribution of the electron-ion IBS heating is about equal to the contribution of the electron-electron IBS mainly obtained in the wiggler and proportional to its length. Therefore, an increase of the electron ring circumference allows an increase in the number of bunches, a decrease the ion heat loading per bunch and a reduction of the wiggler length. Under the given prices per unit length, this allows choosing an optimal ring circumference and an optimal length of the wiggler. The wiggler parameters can be significantly relaxed at the price of reducing the longitudinal cooling rate by $\simeq 3$ times. For the cooling time estimations we use the following wiggler parameters: the length is 40 meters, the maximal magnetic field is 3.6 Tesla. This field corresponds to 5 cm curvature radius. And beta-functions in the wiggler are about 15 cm. The parameters are taken in agreement with conventional ones [6].

The required horizontal emittance could be fixed by a redistribution of the radiation rate between the horizontal and longitudinal degrees of freedom. In order to have this possibility, sufficiently long arc sections are required. Here, two arc sections with the curvature radius $R_a = 1$ m and the angle 5π per each is suggested.

A sketch of the proposed electron cooler is shown in the figure (1).

The main parameters of the electron ring are presented in the table. All the needed parameters for electron cooling time calculations of the RHIC are taken from [7].

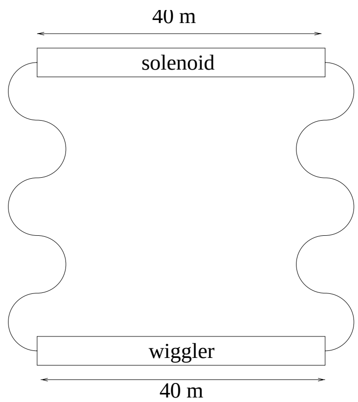

Figure 1: Sketch of the electron ring for electron cooling.

MAIN PARAMETERS OF THE ELECTRON COOLER	
Energy E_e (MeV)	55.4
Relativistic factor γ	108.4
Electrons per bunch N	$1.5 \cdot 10^{10}$
Bunch length σ_{es} (cm)	15
Number of bunches n_b	60
Circumference C (m)	200
Radiation damping time:	
longitudinal (s)	0.014
horizontal (s)	0.12
vertical (s)	0.038
Momentum compaction factor α	0.15
Synchrotron tune ν_s	0.01
Relative energy spread δ_{eE}	$2.9 \cdot 10^{-4}$
Hor. rms emitt., unnorm. ϵ_x(cm)	$4 \cdot 10^{-5}$
Vert. rms emitt., unnorm. ϵ_y(cm)	$2 \cdot 10^{-7}$
Solenoid, length(m) / field(Gs)	40 / 390
Wiggler, length(m) / field(T)	40 / 3.6
Lifetime (min)	0.6
Ion $\beta-$functions in solenoid (m)	160
Electron angles in solenoid	$\leq 1 \cdot 10^{-5}$
Ions longitudinal cooling time (min)	8
Ions transverse cooling time (min)	28

4 Conclusion

The suggested scheme of the electron cooling would help to prevent the beam loss due to the longitudinal IBS and to reduce transverse emittances several times. In the result, the integrated luminosity for the gold beams might be significantly increased.

5 Acknoledgements

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